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Bencuya et al.

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(54) **VERTICAL MOSFET WITH ULTRA-LOW RESISTANCE AND LOW GATE CHARGE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(22) Filed: **Aug. 16, 2000**

(51) Int. Cl.⁷ **H01L 29/76**

(52) U.S. Cl. **257/330; 257/331; 257/341; 257/342**

(58) Field of Search 257/328-334,
257/341, 342; 438/268-274

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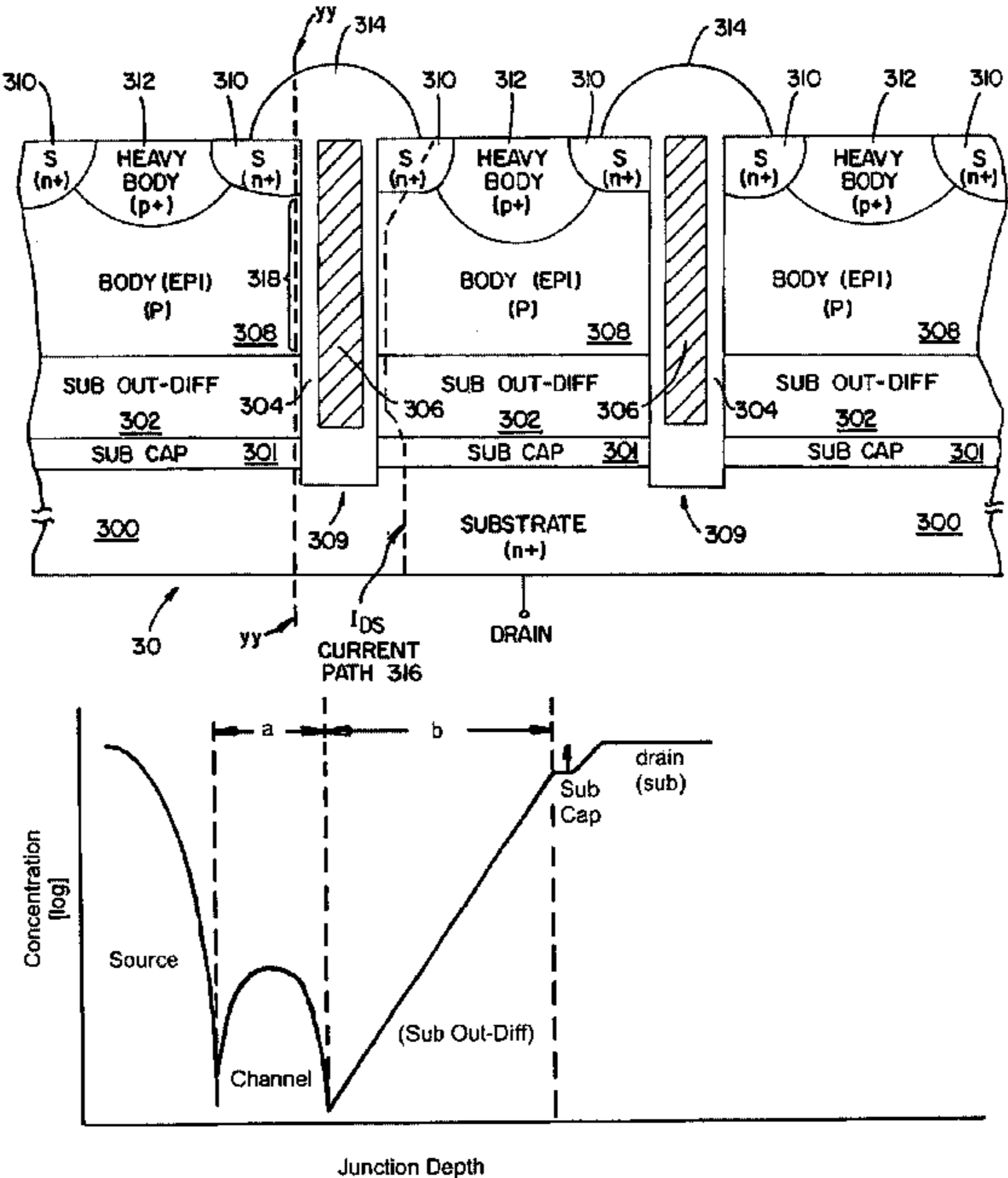
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(57) **ABSTRACT**

A vertical trench double-diffused metal-oxide-semiconductor (DMOS) field effect transistor characterized by a reduced drain-to-source resistance and a lower gate charge and providing a high transconductance and an enhanced frequency response.

10 Claims, 9 Drawing Sheets



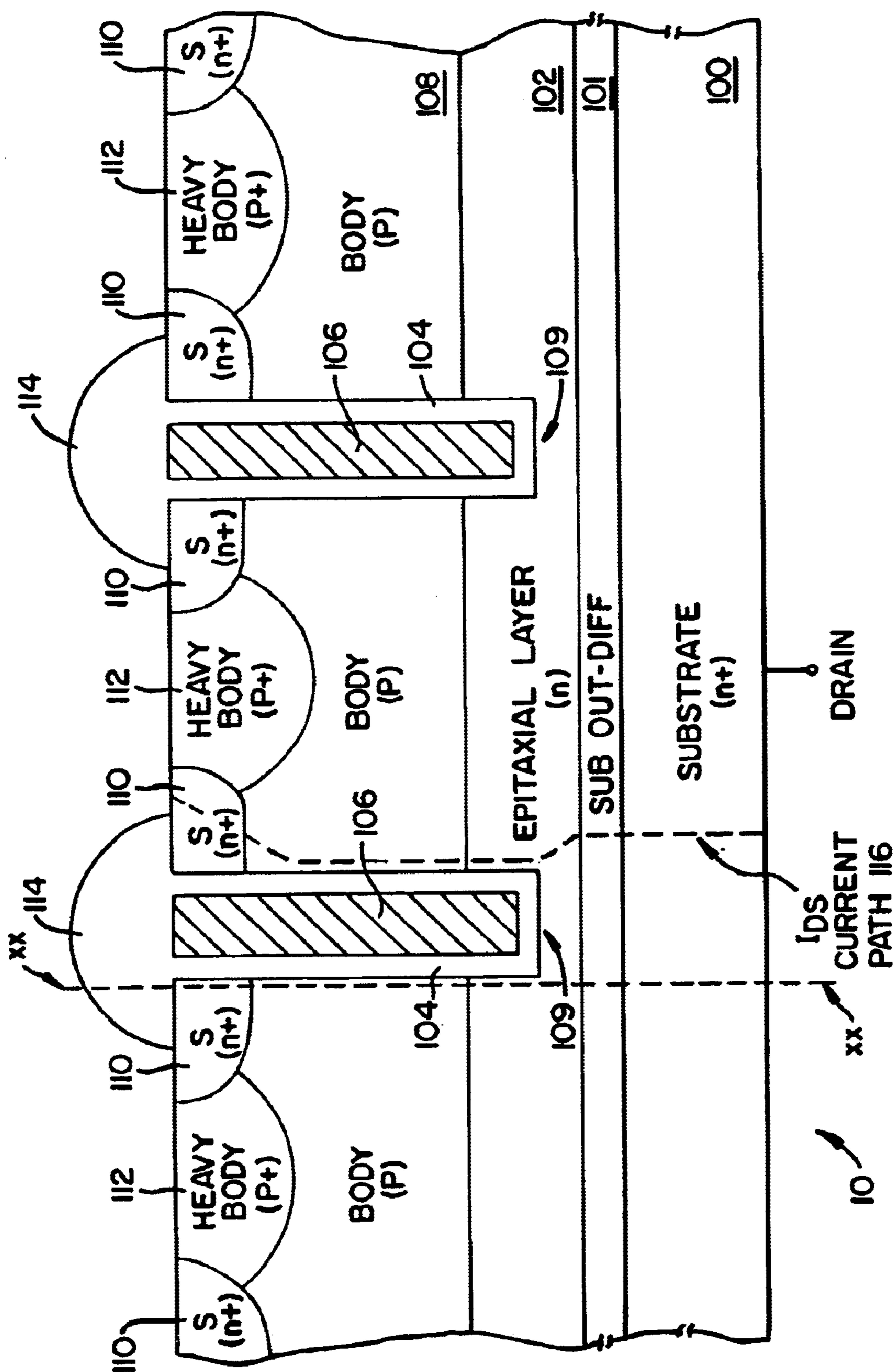


FIG. 1 (PRIOR ART)

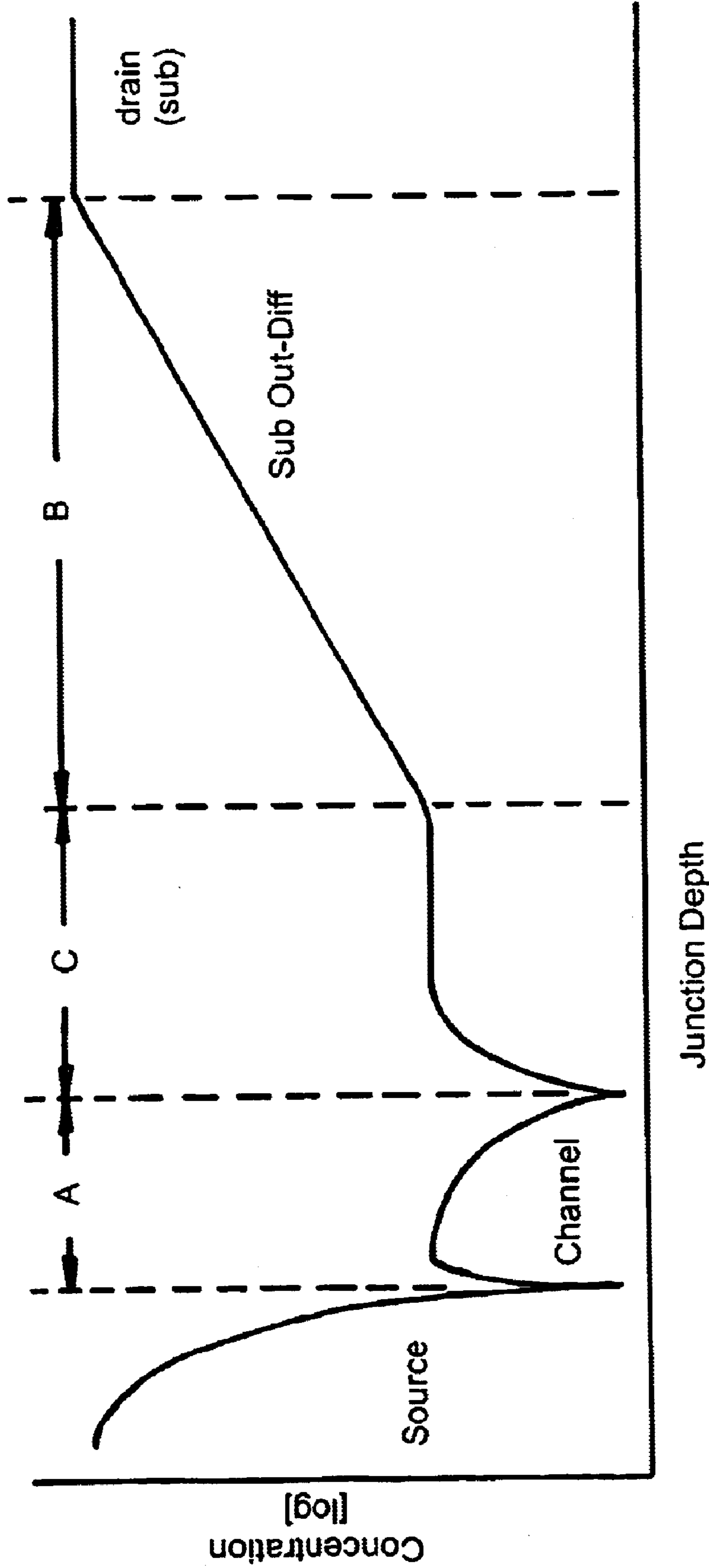


FIG 2
(PRIOR ART)

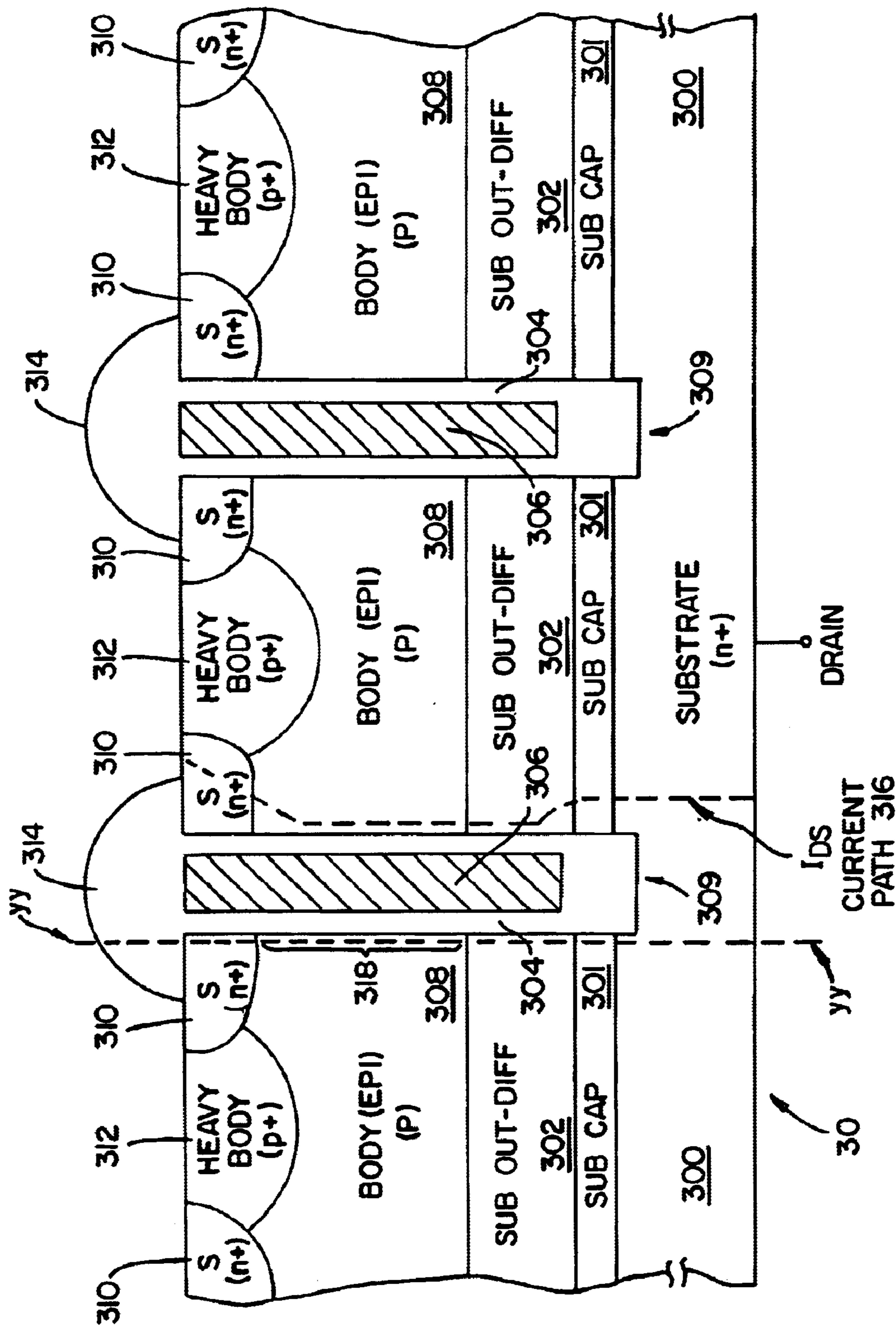


FIG. 3

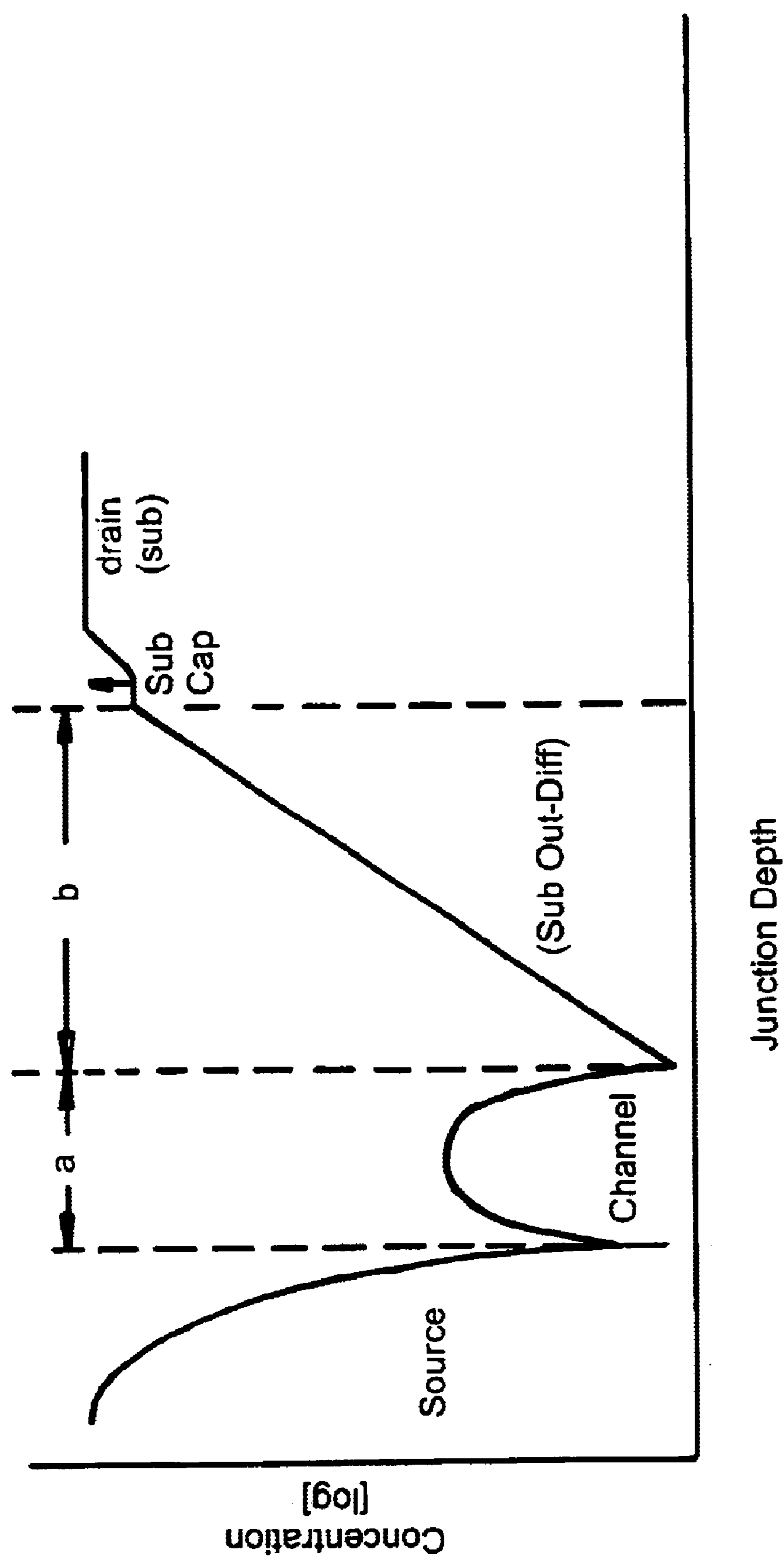
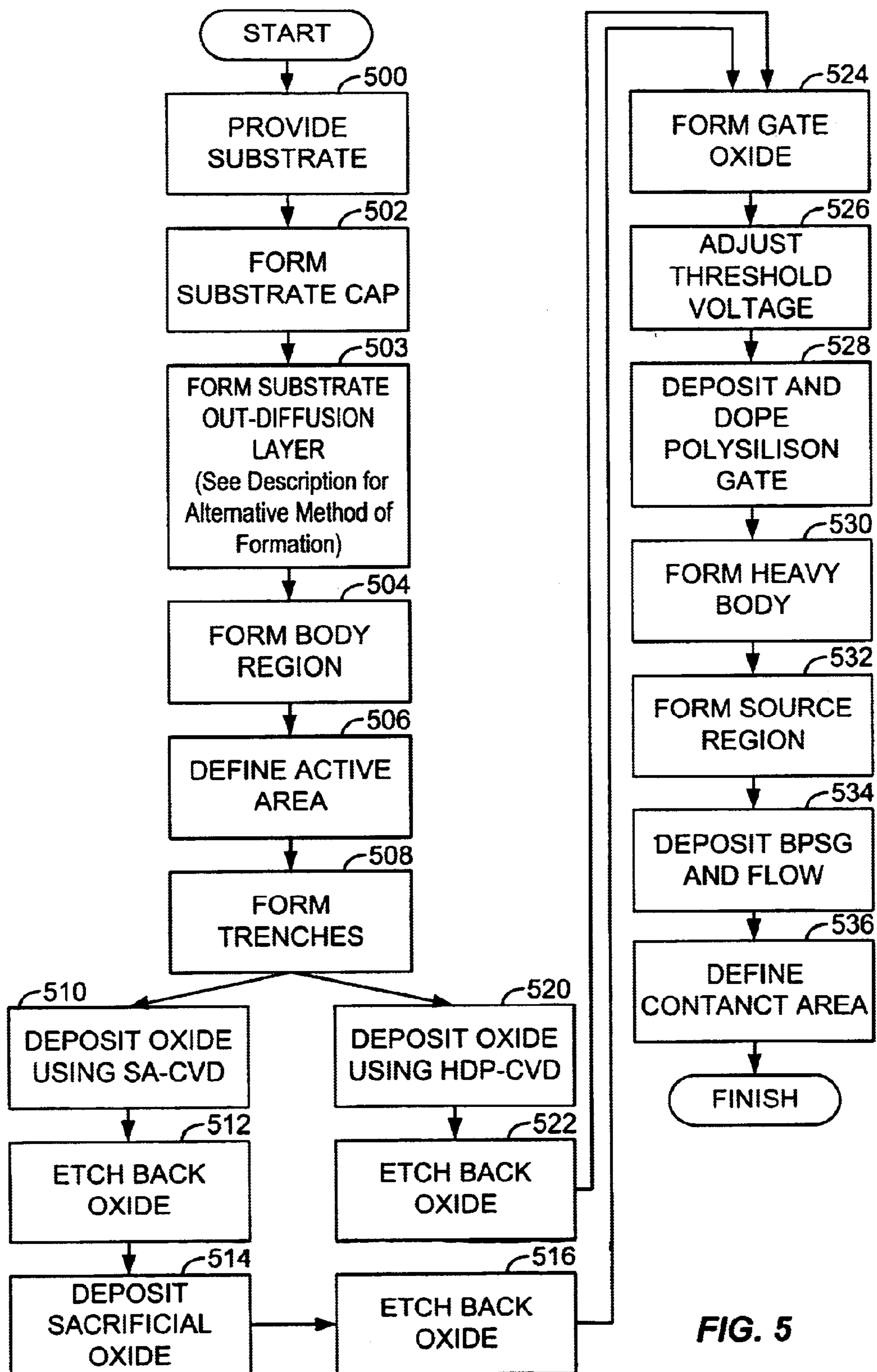


FIG. 4

**FIG. 5**

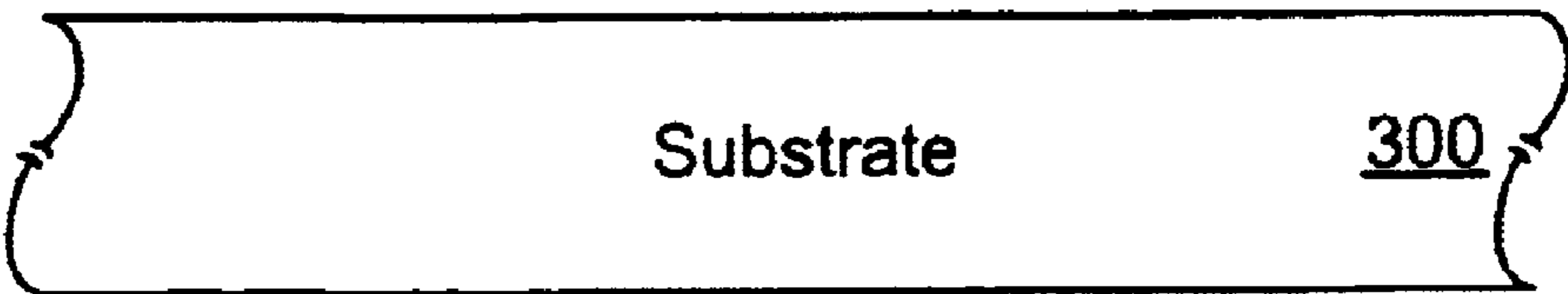


FIG. 6A

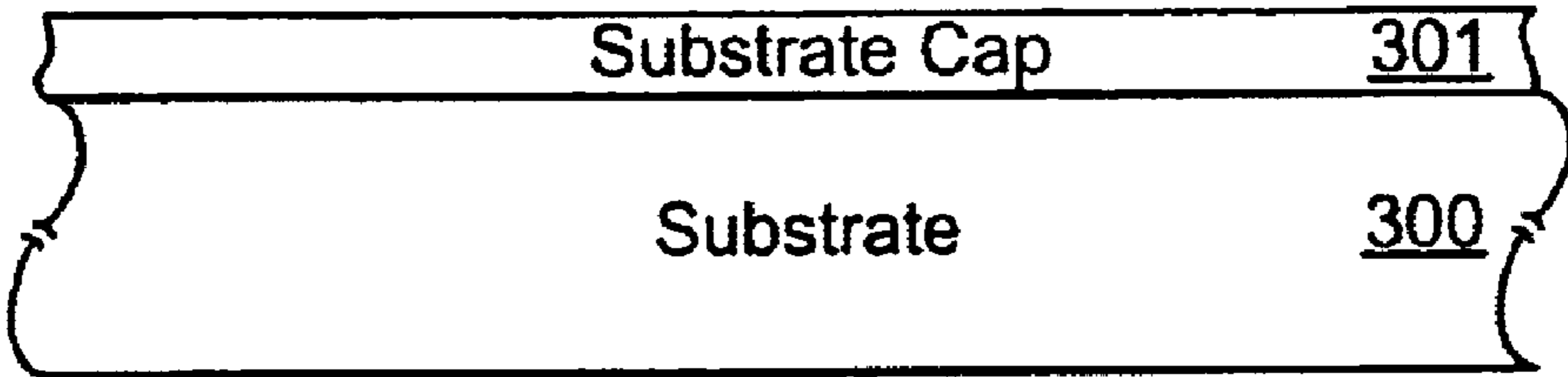


FIG. 6B

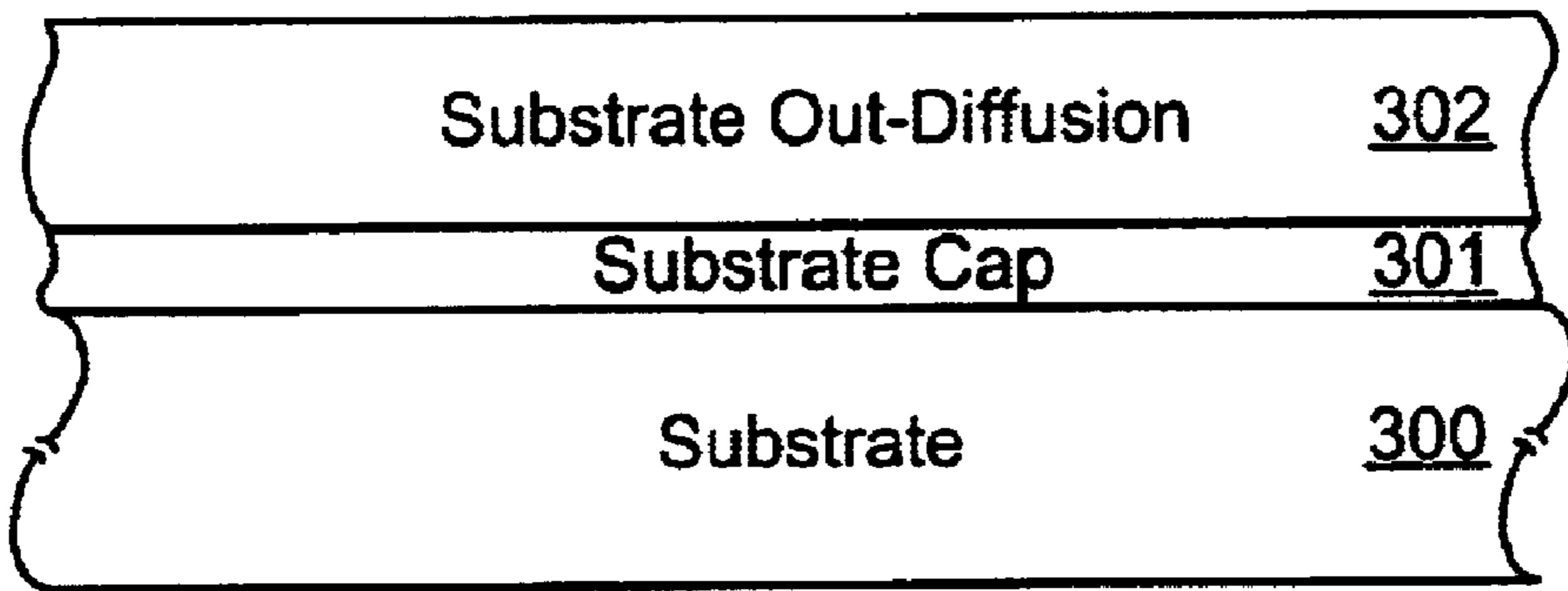


FIG. 6C

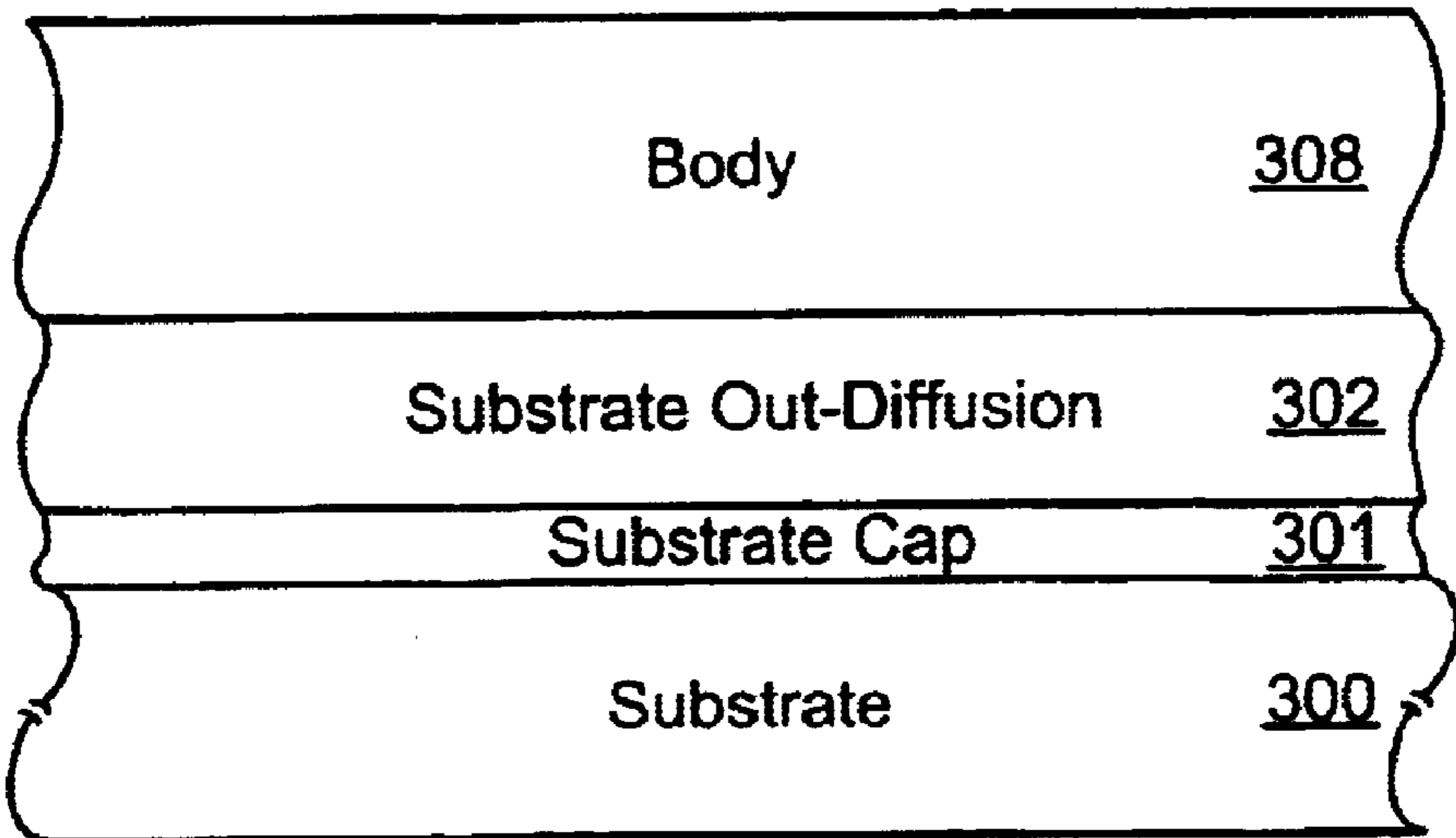


FIG. 6D

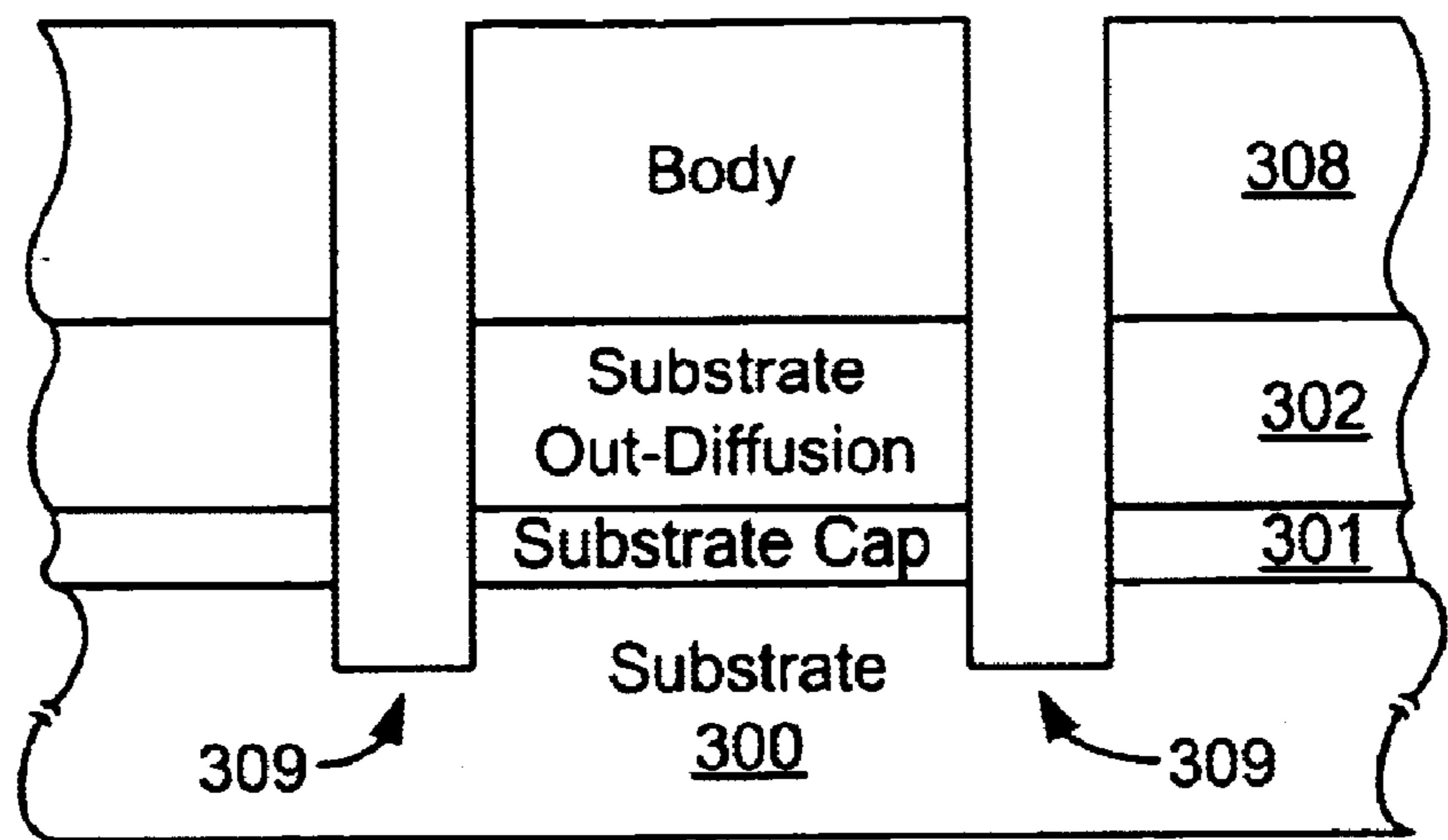


FIG. 6E

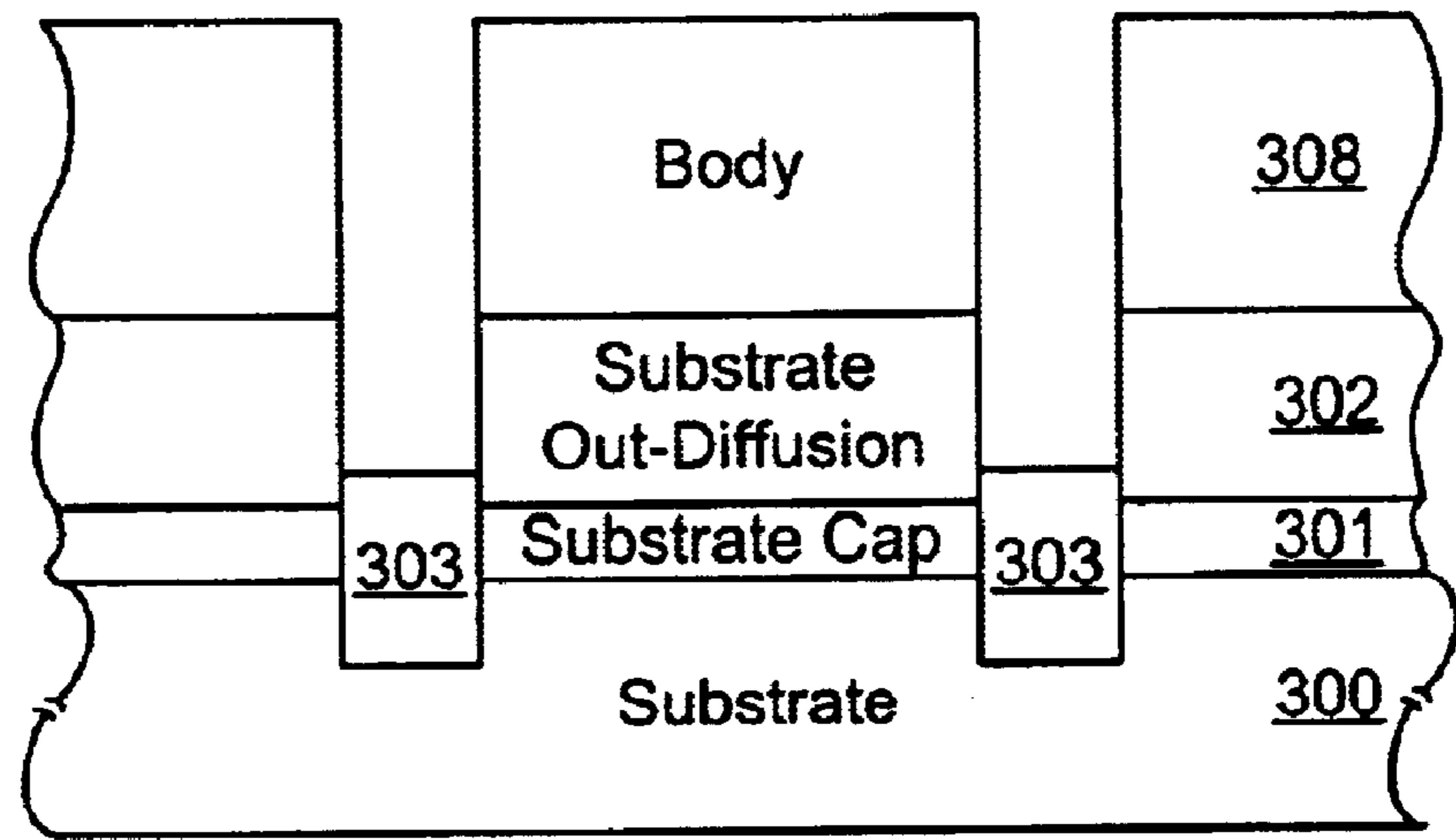


FIG. 6F

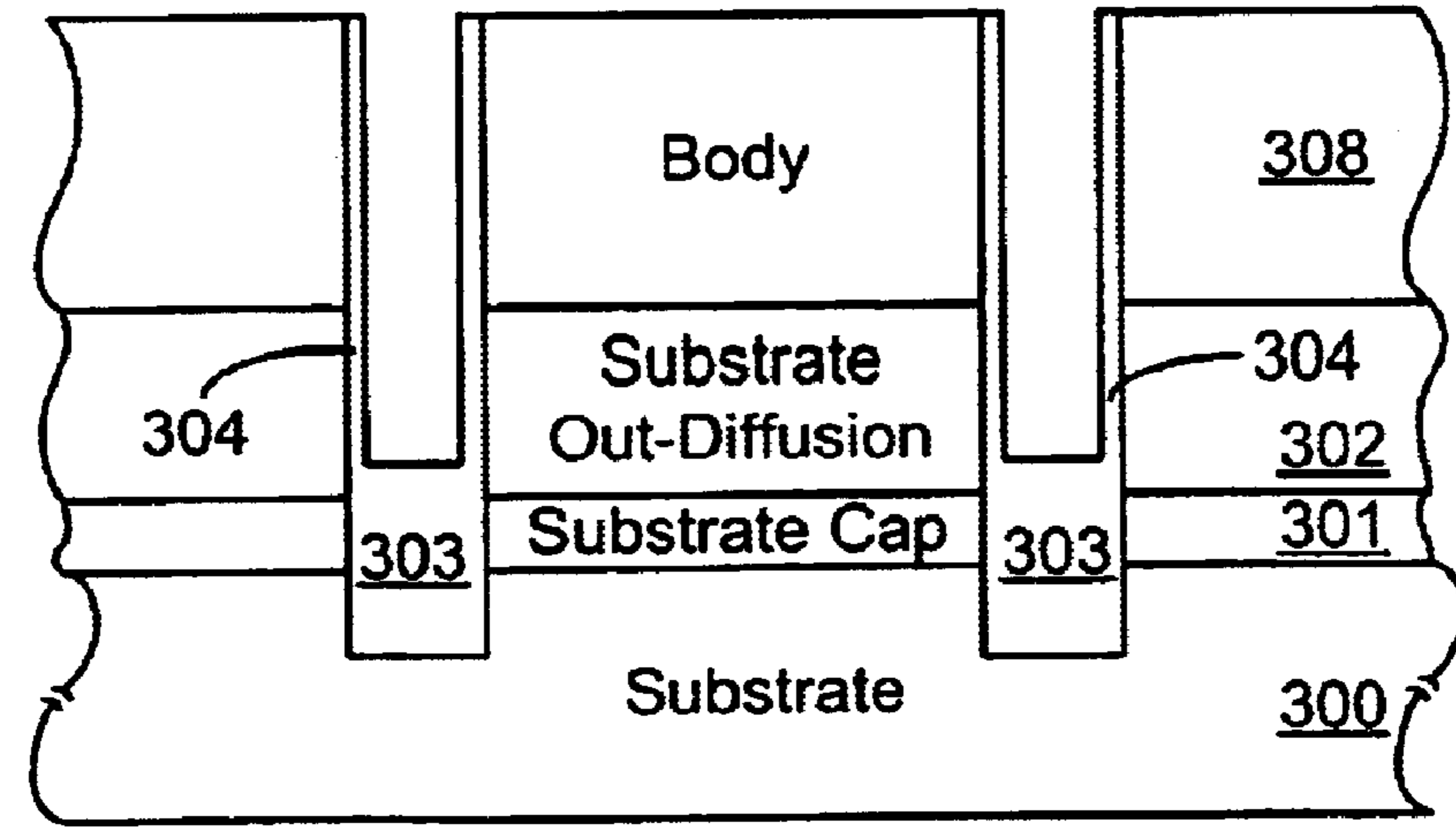


FIG. 6G

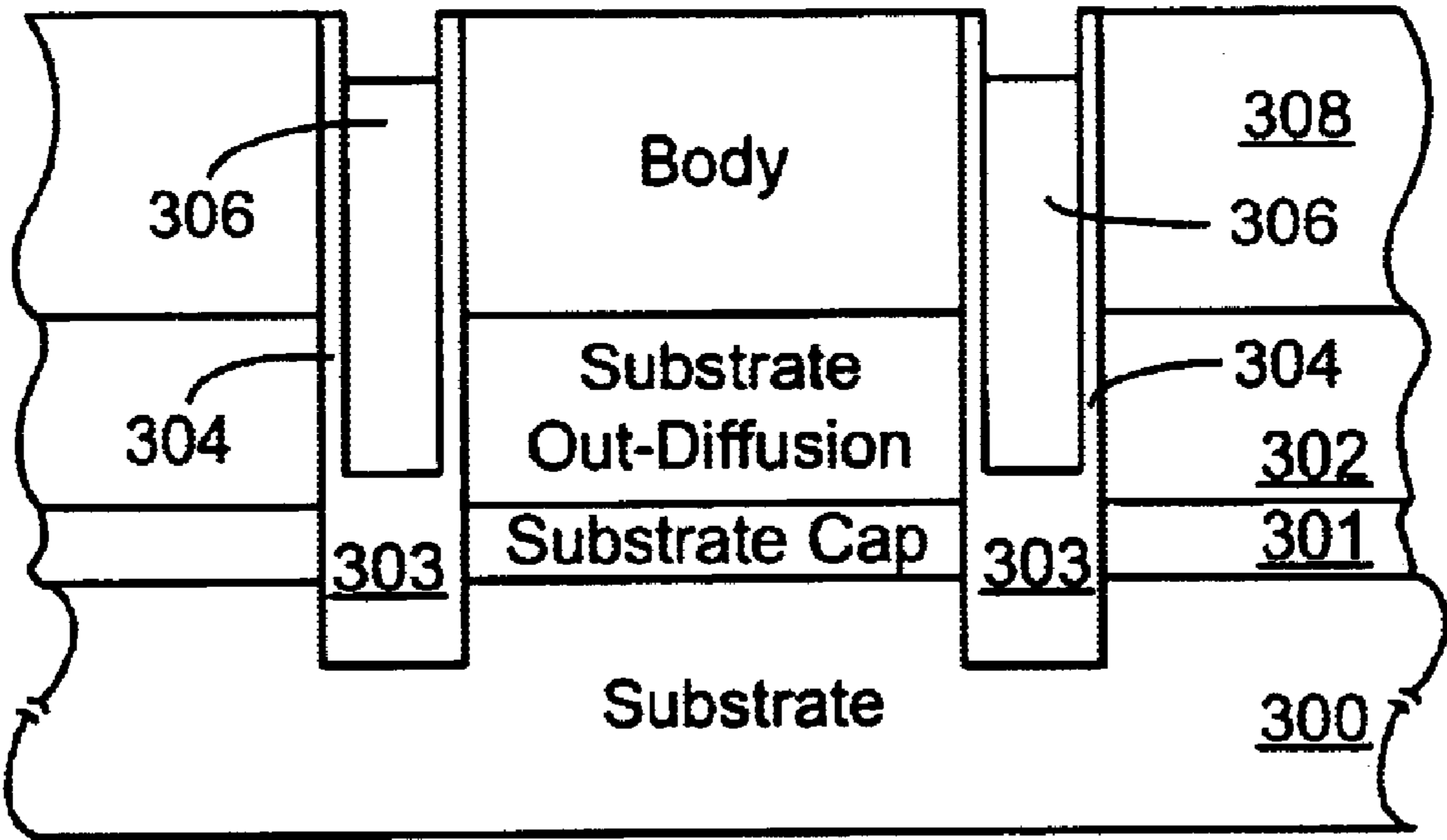


FIG. 6H

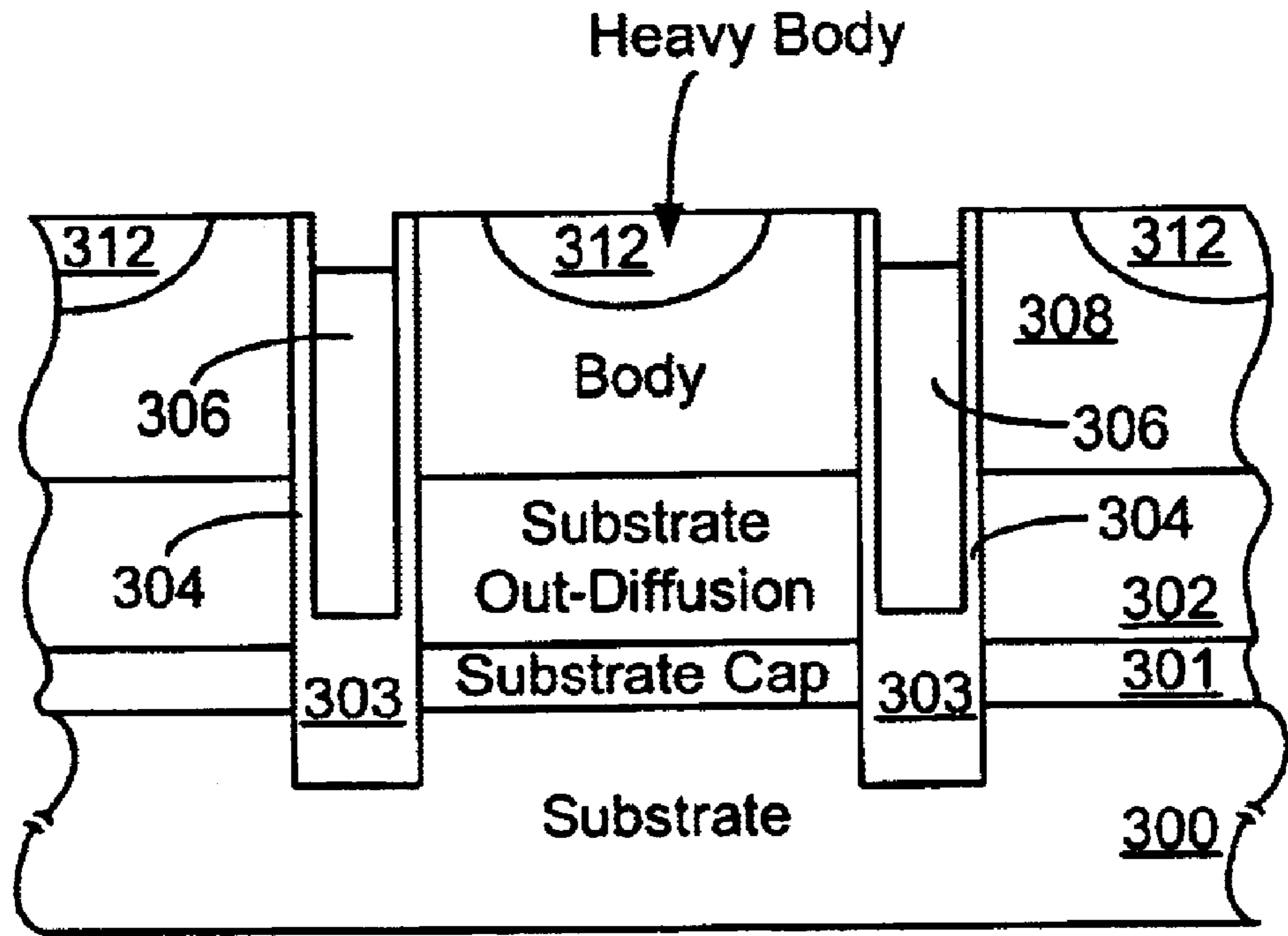


FIG. 6I

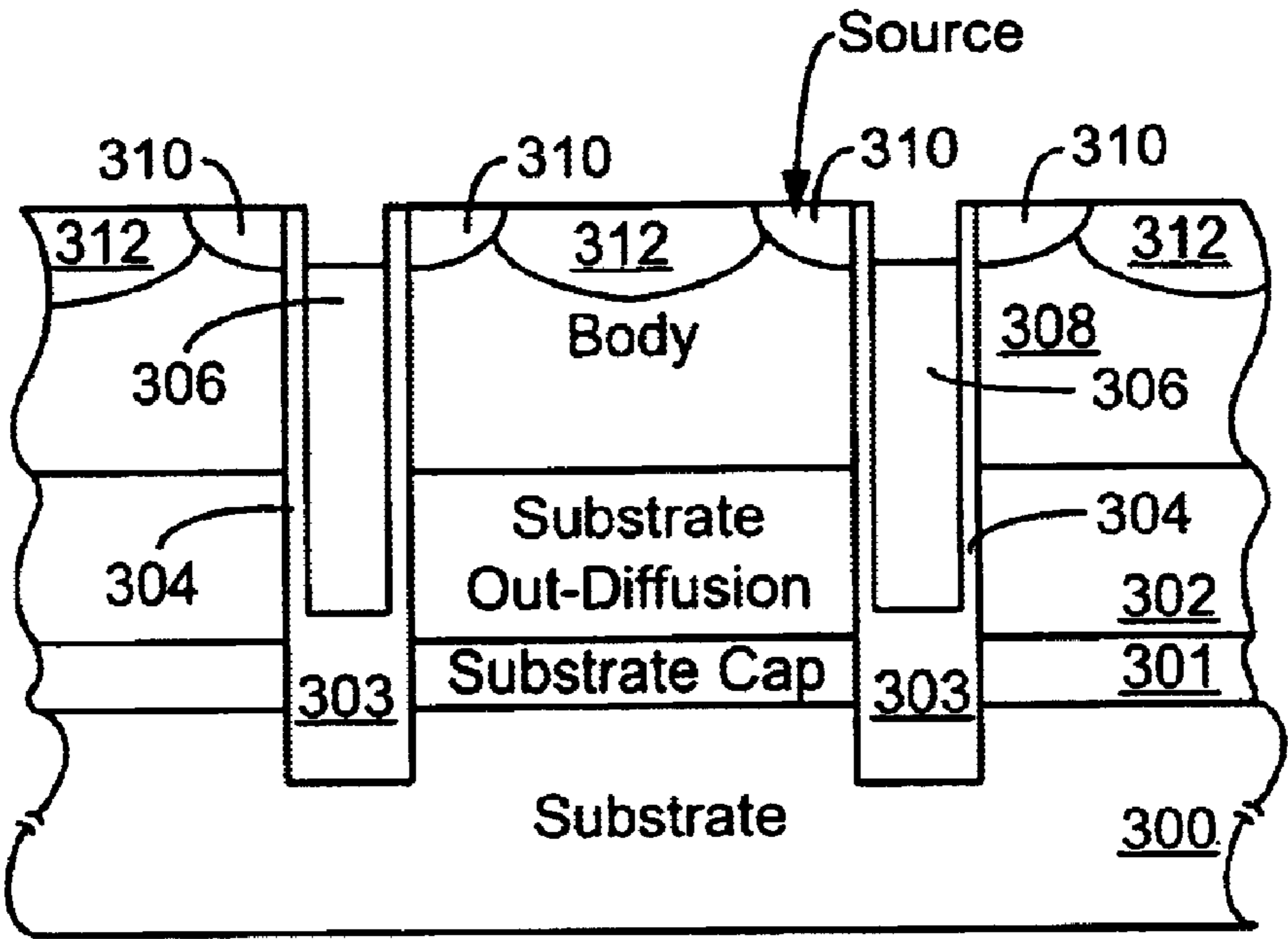


FIG. 6J

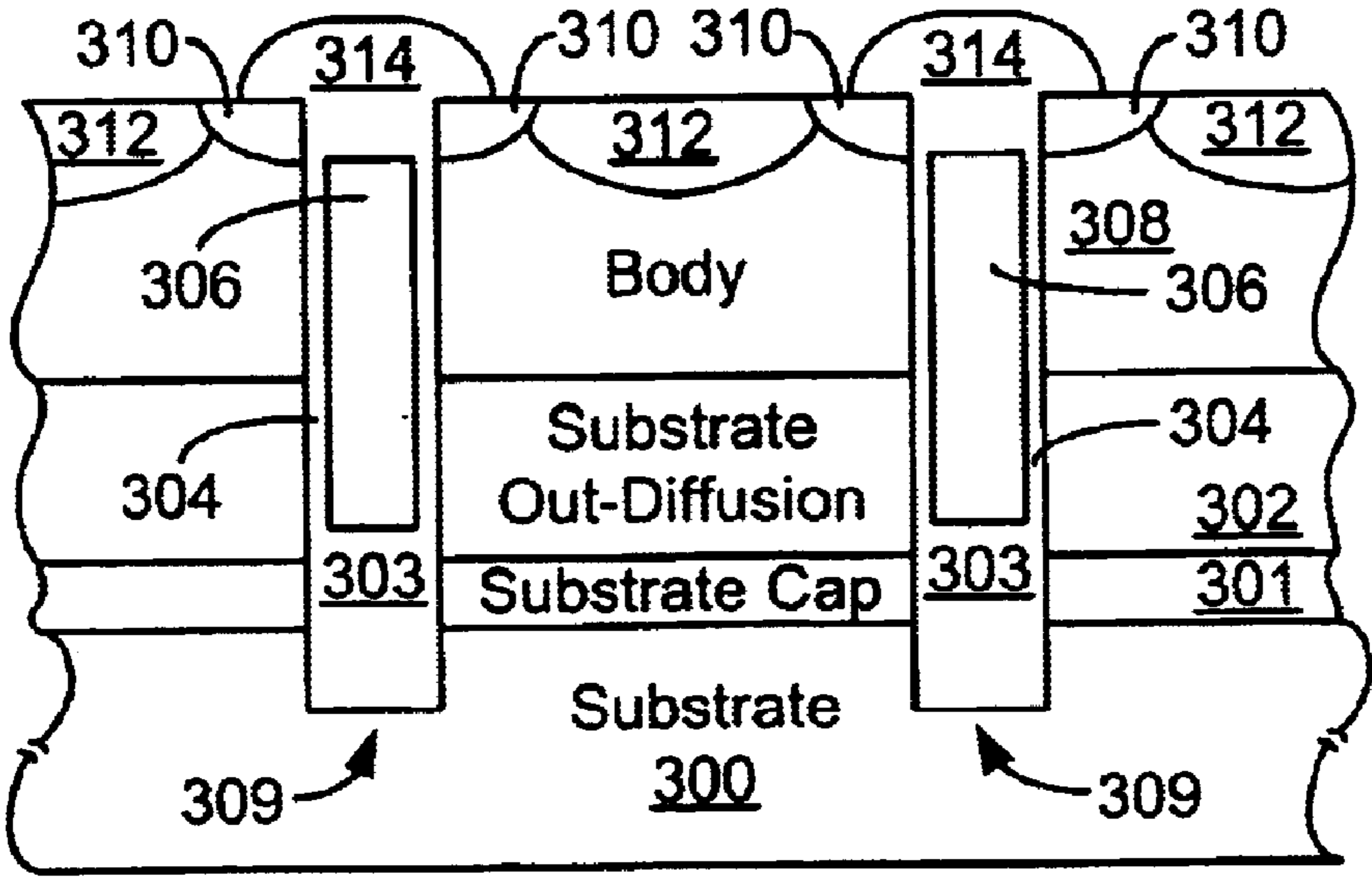


FIG. 6K

VERTICAL MOSFET WITH ULTRA-LOW RESISTANCE AND LOW GATE CHARGE

CROSS-REFERENCES TO RELATED APPLICATIONS

A first related application is filed concurrently with the present application as U.S. patent application Ser. No. 09/640,954 in the names of Henry W. Hurst et al., and entitled "A Method of Creating Thick Oxide on the Bottom Surface of a Trench Structure in Silicon" and assigned to the present assignee. A second related application is filed concurrently with the present application as U.S. patent application Ser. No. 09/640,496 in the name of James J. Murphy, and entitled "Selective Oxide Deposition in the Bottom of a Trench" and assigned to the present assignee. Both of these applications are incorporated by reference herein for all purposes.

BACKGROUND OF THE INVENTION

The present invention relates to field effect transistors (FETs) and, in particular, to trench double-diffused metal-oxide-semiconductor (DMOS) transistors and methods of fabricating the same.

Power Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) are well known in the semiconductor industry. One type of MOSFET is a double-diffused trench MOSFET, or what is known as a "trench DMOS" transistor. A cross-sectional view of a portion of a typical n-channel trench DMOS transistor **10** is shown in FIG. **1**. It should be pointed out that the relative thickness of the various layers are not necessarily drawn to scale.

The trench DMOS transistor **10**, shown in FIG. **1**, includes an n-type substrate **100** over which a substrate out-diffusion layer **101** is formed. An n-type epitaxial layer **102** is formed over substrate out-diffusion layer **101** and a p-type body layer **108** covers epitaxial layer **102**. One or more trenches **109** extend through the body layer **108** and a portion of the epitaxial layer **102**. Gate oxide layer **104** lines the sidewalls and bottom of each trench **109** and a conductive material **106**, typically doped polysilicon, lines gate oxide layer **104** and fills each trench **109**. N+ source regions **110** flank each trench **109** and extend a predetermined distance into body layer **108**. Heavy body regions **112** are positioned within body layer **108**, between source regions **110**, and extend a predetermined distance into body layer **108**. Finally, dielectric caps **114** cover the filled trenches **109** and also partially cover source regions **110**. Note that trench DMOS transistor **10** also typically includes one or more metal layers, which contact source regions **110**, with adjacent metal layers separated by an insulating material. These metal layers are not shown in FIG. **1**.

FIG. **2** shows a doping concentration profile, taken along a cross-section labeled "xx" in FIG. **1**. Cross section xx is representative of the resistance path **116** that a drain-to-source current, I_{DS} , encounters as charge carriers travel from source region **110** to the drain of trench DMOS transistor **10**, when trench DMOS transistor is on. The various regions that comprise path **116** are source region **110**, body region **108**, epitaxial layer **102**, substrate out-diffusion layer **101** and substrate **100**.

The resistance encountered by I_{DS} due to the presence of these various regions is typically quantified as the drain-to-source resistance, $R_{DS(on)}$. A high drain-to-source resistance, i.e. $R_{DS(on)}$, limits certain performance characteristics of the transistor. For example, both the transconductance, g_m , of the device, which is a measure of

the current carrying capability of the device (given a certain gate voltage) and the frequency response of the device, which characterizes the speed of the device, are reduced the higher $R_{DS(on)}$ is. Another factor that limits the speed of the trench DMOS transistor is the gate oxide charge, Q_g . The higher Q_g is the larger the gate-to-drain overlap capacitance becomes and, consequently, the lower the switching capability of the device becomes.

Because the drain-source voltage is dropped almost entirely across the channel region, which comprises the body and epitaxial layers, the channel length, channel resistance and channel concentration profile are critical characteristics that affect the operating performance of a trench MOSFET. Whereas the absolute values of these characteristics are important, so too is the controllability of their variation. Wide device-to-device variations negatively affect the reproducibility of a device having desired performance capabilities.

SUMMARY OF THE INVENTION

Generally, according to an exemplary embodiment of the present invention a trench DMOS transistor and its method of manufacture is provided. The trench DMOS transistor is characterized by an ultra-low on resistance (i.e., $R_{DS(on)}$) and a low gate charge. The method of manufacture minimizes variations in the transistor characteristics by controlling out-diffusion from the substrate.

In a first aspect of the invention, a trench DMOS transistor is disclosed. In an exemplary embodiment the trench DMOS transistor comprises a substrate having a first conductivity type that embodies a drain layer of the transistor, the substrate having a substrate doping concentration; a substrate out-diffusion layer formed over the substrate, the substrate out-diffusion layer having a first major surface closest to the substrate that has a doping concentration approximately equal to that of the substrate doping concentration and a second major surface having a lower concentration than the substrate doping concentration; a body region having a second conductivity type, which is epitaxially formed over the substrate; at least one trench having a bottom and sidewalls, each trench extending through the substrate out-diffusion layer and the body region; a dielectric material lining the sidewalls and bottom of the at least one trench; a conductive material lining the dielectric material and substantially filling the trenches; and source regions having the first conductivity type positioned next to each trench within the body region.

In a second aspect of the invention, a substrate cap layer is positioned between the substrate and the substrate out-diffusion layer in the trench DMOS transistor described in reference to the first aspect of the invention.

In a third aspect of the invention, the thickness of the dielectric material at the bottom of the trenches is thicker than a thickness of the dielectric material on the sidewalls of the trenches so that improved gate charge performance is realized.

In a fourth aspect of the invention, a method of fabricating a trench DMOS transistor is disclosed. The method comprises providing a substrate having a first conductivity type that embodies a drain layer of the transistor, the substrate having a substrate doping concentration; forming a substrate out-diffusion layer over the substrate, the substrate out-diffusion layer having a first major surface closest to the substrate that has a doping concentration approximately equal to that of the substrate doping concentration and a second major surface having a lower concentration than the

substrate doping concentration; forming a body region having a second conductivity type over the substrate; forming one or more trenches through the substrate out-diffusion layer and the body region, each trench having a bottom and sidewalls; forming a dielectric plug at the bottom of each trench; lining the sidewalls and bottom of each trench with a dielectric material; lining the dielectric material with a conductive material and substantially filling the trenches with the conductive material; and forming source regions having the first conductivity type positioned next to each trench within the body region.

In a fifth aspect of the invention, the dielectric plug described in reference to the fourth aspect of the invention is formed either by high density plasma chemical vapor deposition or sub-atmospheric chemical vapor deposition.

A further understanding of the nature and advantages of the inventions herein may be realized by reference to the remaining portions of the specification and the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a cross-sectional view of a conventional trench DMOS transistor;

FIG. 2 shows a doping concentration profile, taken along a cross-section labeled "xx" in FIG. 1, of the trench DMOS transistor shown in FIG. 1;

FIG. 3 shows a cross-sectional view of an exemplary n-channel trench DMOS transistor **30** according to one embodiment of the present invention;

FIG. 4 shows an exemplary doping concentration profile, taken along a cross-section labeled "yy" in FIG. 3, of the trench DMOS transistor shown in FIG. 3;

FIG. 5 shows an exemplary process flow, according to another aspect of the invention, for fabricating the trench DMOS transistor shown in FIG. 3; and

FIGS. 6A–6K show cross-sectional views of the formation of the trench DMOS transistor according to the process flow shown in FIG. 5.

DESCRIPTION OF THE SPECIFIC EMBODIMENTS

The present invention is directed at a trench MOSFET device, and its method of manufacture, that can be used in applications such as cellular phone power supplies, battery switching. The trench MOSFET of the present invention is defined by a structure having a low drain-to-source resistance, low gate charge and a method of fabrication that minimizes device-to-device variations in operating characteristics by controlling out-diffusion from the transistor substrate.

FIG. 3 shows a cross-sectional illustration of an exemplary n-channel trench DMOS transistor **30** according to one embodiment of the present invention. Trench DMOS transistor **30** includes an n-type substrate **300**, which has a resistivity of, for example, 1–5 mΩ-cm, over which a substrate cap layer **301** is formed. Substrate cap layer **301** is heavily doped and has a resistivity of, for example, 1 mΩ-cm. Substrate cap layer **301** functions to provide a more constant resistivity range than what substrate vendors typically guarantee. For example, substrate vendors typically guarantee that the resistivity of an Arsenic n-type substrate be only somewhere within the range of 1–5 mΩ-cm. As explained below, the more precisely controlled resistivity of substrate cap layer **301**, relative to substrate resistivities, ensures a more predictable and stable channel length.

A substrate out-diffusion layer **302** is formed over substrate cap layer **301**. Substrate cap layer **301** functions to better control and reduce the channel length of trench DMOS transistor **30** by inhibiting substrate out-diffusion. Better control of the channel length leads to a more predictable and reproducible $R_{DS(on)}$, Q_g and breakdown voltage. A p-type body **308** is formed over substrate out-diffusion layer **302**. The thickness and resistivity of p-type body are, for example, 4 μm and 0.1 Ω-cm, respectively. One or more trenches **309** extend through the body layer **308**, substrate out-diffusion layer **302**, substrate cap layer **301** and, preferably, a portion of substrate **300**. Gate oxide layer **304** lines the sidewalls and bottom of each trench **309** and a conductive material **306**, for example, doped polysilicon, lines gate oxide layer **304** and fills each trench **309**. The thickness of gate oxide layer **304** is preferably thicker at the bottom of each trench **309** than on the sidewalls of the trench **309**.

N+ source regions **310** flank each trench **309** and extend a predetermined distance into body layer **308**. Heavy body regions **312** are positioned within body layer **308**, between source regions **310**, and extend a predetermined distance into body layer **308**. Finally, dielectric caps **314** cover the filled trenches **309** and also partially cover source regions **310**.

Trench DMOS transistor **30** also includes one or more metal layers, which contact source regions **310**, with adjacent metal layers separated by an insulating material. These metal layers are not shown in FIG. 3.

Comparing trench DMOS transistor **30** to the trench DMOS transistor **10** in FIG. 1 reveals some important distinctions. First, as was described above, it is preferred that the thickness of gate oxide layer **304** be larger at the bottoms of each trench **309** than on the sidewalls of each trench **309**. The reason for this is that a thicker gate oxide at the bottom of trenches **309** alleviates high electric fields in the vicinity of the bottom of trenches **309**, thereby providing a higher breakdown voltage, BV_{dss} . The relatively greater thickness also has the effect of reducing the drain overlap capacitance, so that the gate charge, Q_g , is reduced.

Second, trench DMOS transistor **30** does not incorporate an n-type epitaxial layer as trench DMOS transistor **10** does (see, layer **102** in FIG. 1). The primary purpose of the epitaxial layer is to provide a region for depletion to avoid reach through. However, while not necessarily limited to, the trench DMOS transistor of the present invention is envisioned to be mainly for low voltage applications. A benefit of the absence of any n-type epitaxial layer in trench DMOS transistor **30** is that a reduced current path is realized so that $R_{DS(on)}$ is lowered. As explained above, a lower $R_{DS(on)}$ improves certain performance capabilities of the device, which are characterized by, for example, a higher transconductance, g_m , and an improved frequency response.

Finally, body **308** is formed by epitaxial deposition, as compared to an implant/diffusion process as used in the manufacture of the trench DMOS transistor shown in FIG. 1. The diffusion step in the manufacture of a trench DMOS is typically performed at high temperature and operates to drive all junctions, including the substrate out-diffusion layer **102**, for example, in the trench DMOS transistor shown in FIG. 1. A typical diffusion cycle used in the manufacture of the trench DMOS transistor **10** of FIG. 1 can result in a substrate out-diffusion layer thickness of over 2 μm. Because a diffusion cycle is not required for forming body **308** of trench DMOS transistor **30**, the thickness of substrate out-diffusion layer **302** can be made much thinner,

for example approximately less than or equal to $1\ \mu\text{m}$. Moreover, for a given channel length, channel **318** can hold more charge than that of a conventional trench DMOS transistor having a body formed using an implant/diffusion process. Because the channel **318** of trench DMOS transistor **30** can hold more charge, it is less likely that drain-to-source punch-through will occur. Hence, the channel length of channel **318** of trench DMOS **30** can be reduced. The reduction in length of channel **318** and substrate out-diffusion layer **302**, reduce the overall distance of the drain/source path, so that a lower $R_{DS(on)}$ is realized.

Referring now to FIG. 4, there is shown an exemplary doping concentration profile, taken along a cross-section labeled “yy,” for the trench DMOS transistor **30** shown in FIG. 3. Comparing this doping profile to the doping profile of a conventional trench DMOS transistor, shows that (1) there is no n-type epitaxial layer used in the trench DMOS transistor **30** of the present invention; (2) the channel length of the trench DMOS transistor **30** of the present invention is shorter; and (3) the substrate out-diffusion layer is shorter and has a steeper concentration gradient for the trench DMOS transistor **30** of the present invention. All of these characteristics have the effect of reducing the overall drain to source current path, thereby making $R_{DS(on)}$ smaller.

Referring now to FIG. 5, there is shown an exemplary process flow, according to another aspect of the invention, for fabricating a trench DMOS transistor. This process flow can be used, for example, to fabricate the trench DMOS transistor shown in FIG. 3. The process flow shown in FIG. 5 will now be described in reference to FIGS. 6A through 6K.

The first step, **500**, a substrate **300**, having a resistivity of, for example 1 to $5\ \text{m}\Omega\text{-cm}$ is provided. This is shown in FIG. 6A. Next, in step **502**, a substrate cap layer **301** is formed over the substrate **300**. Substrate cap layer **301** has a resistivity of, for example less than or approximately equal to $1\ \text{m}\Omega\text{-cm}$ and a thickness of approximately $1\ \mu\text{m}$. The structure following step **502** is shown in FIG. 6B.

Following formation of cap layer **301** in step **502** a substrate outdiffusion layer **302** is formed over substrate cap layer **301**. This is shown in FIG. 6C. In an alternative embodiment, an out-diffusion layer is formed coincidentally as various high-temperature processing steps (e.g. steps **530** and **532** in FIG. 5) are performed later in the fabrication process. In step **504** a p-type body region **308** is formed over substrate out-diffusion layer **302**. Body region is formed, for example, using an implant and drive in process, using boron as the dopant with a dose of about $1\text{E}12$ to $1\text{E}15\ \text{cm}^{-2}$. Following the drive in, body region **308** has a depth of approximately $4\ \mu\text{m}$. The structure following step **504** is shown in FIG. 6D. Next, in step **506** an initial oxide layer is formed over the p-type body region **308**, over which an active area of transistor **30** is defined using, for example, standard photolithography.

After the active area has been defined, in step **508** trenches **309** are formed. Preferably, an anisotropic etch is used to create trenches **309**. The anisotropic etch is in the form of a plasma, which is an almost neutral mixture of energetic molecules, ions and electrons that have been excited in a radio-frequency electric field. Different gases are used depending on the material to be etched. The principal consideration is that the reaction products must be volatile. For etching silicon, the reactants may be, for example, He:O_2 , NF_3 and HBr the pressure may be, for example, $140\ \text{mTorr}$ and the duration of the etch may be approximately 3 minutes. In this example, the trenches have

a depth of approximately $2.5\ \mu\text{m}$. As shown in FIG. 6E, each trench **309** extends vertically downward from an exposed surface of body region **308**, into and through body region **308**, through substrate out-diffusion layer **302**, through substrate cap layer **301** and partially into substrate **300**.

Next in the process, an oxide plug **303** is formed at the bottom of each trench **309**. These oxide plugs **303** can be formed in a variety of ways. In a first embodiment of the invention to this regard, in step **510**, sub-atmospheric chemical vapor deposition (SA-CVD) is used to deposit oxide on the sidewalls, bottom and over the upper and lower corners of each trench **309**. Then, in step **512**, the oxide is etched back so that only an oxide plug **303** remains at the bottom of each trench **309**. At this stage in the process a sacrificial oxide, having a thickness of about $500\ \text{\AA}$ may be deposited (step **514**) and then stripped (step **516**) to prepare the trench sidewalls for a gate oxide. These sacrificial oxide and strip steps are optional. The oxide plug **303** can be alternatively formed using a process known as high-density plasma chemical vapor deposition (HDP-CVD). Using this process, in step **520**, oxide is deposited on the sidewalls, bottom and over the upper and lower corners of each trench **309**. Then, in step **522**, the oxide is etched back using a wet etch to leave an oxide plug **303** at the bottom of each trench **309**. The structure following formation of oxide plugs **303** is shown in FIG. 6F.

Next, in optional step **526**, the threshold voltage of the structure can be adjusted by administering a p-type implant having, for example, an energy and dose of $70\ \text{keV}$ and $3\text{E}13\ \text{cm}^{-2}$, respectively.

After trenches **309** are formed with the oxide plugs **303**, a gate oxide **304** is formed on the sidewalls of trenches **309** as is shown in FIG. 6G. The thickness of gate oxide **304** in this example, is preferably about $200\ \text{\AA}$. Following formation of gate oxide **304**, in step **528**, trenches **309** are lined and filled with polysilicon and then doped using, for example, an n-type implant or by administering a conventional POCl_3 doping process. Doping can also be performed using an in-situ process, i.e., as the polysilicon is deposited. The structure following step **528** is shown in FIG. 6H.

Next in another optional step **530**, a p+ heavy body region **312** can be formed between adjacent trenches **309**. In this example, a surface through which heavy body region **312** is to be formed is defined using, for example, conventional photolithography. Through this surface, two separate p-type (e.g., boron) implants are performed, although in some applications a single implant may be sufficient. In this example, a first implant is performed at a dose and energy of, for example, $2\text{E}15\ \text{cm}^{-2}$ and $135\ \text{keV}$, respectively and a second implant is performed at a dose and energy of $5\text{E}14\ \text{cm}^{-2}$ and $70\ \text{keV}$, respectively. The primary purpose of the first implant is to bring the depth of heavy body region **312** as deep as is necessary to compensate for the n+ source region, which is formed later in the process. The second implant has a low energy but a high dose. The purpose of this implant is to extend high concentration of the p+ heavy body from the first implant to the surface so that an ohmic contact can be formed. The dose is made high enough to accomplish this but not so high as to overcompensate the n+ source region, which is formed later in the process. In an alternative embodiment, heavy body region can be formed following a contact defining step (step **536**), which is performed later in the process.

In step **532** a source region **310** is formed. Similar to formation of heavy body region **312**, in this example a double implant is used. In this example, a surface through

which source region **310** is to be formed is defined using, for example, conventional photolithography. Through this surface, two separate n-type implants are performed, although in some applications a single implant may be sufficient. In this example, a first implant of arsenic is performed at a dose and energy of, for example, $8 \times 10^{15} \text{ cm}^{-2}$ and 80 keV, respectively and a second implant of phosphorous is performed at a dose and energy of $5 \times 10^{15} \text{ cm}^{-2}$ and 60 keV, respectively. The purpose of the first implant is to form a source region **310** and the purpose of the second implant is to extend source region **310** to the surface so that a source contact can be formed. The structure following formation of source region **310** is shown in FIG. 6J.

Whereas the above description described formation of heavy body region **312** prior to the formation of source region **310**, in an alternative embodiment the source region could be formed before formation of the heavy body region.

Next, in step **534**, an insulating layer, e.g., borophosphosilicate glass, having a thickness in the range of about 5 to 15 kÅ is deposited over the exposed surface of the entire structure. Then the insulating layer is densified or “flowed”.

In step **536**, the insulating layer is patterned and etched using, for example, standard photolithography, to define electrical contact areas for the trench DMOS structure. As shown in FIG. 6K, the etch is controlled to preserve insulating caps **314** over trenches **309**. Following step **536**, metallization and passivation steps are performed, although they are not shown in the process diagramed in FIGS. 5 and 6. One skilled in the art would understand, however, what is necessary to perform these steps.

Although the invention has been described in terms of a specific process and structure, it will be obvious to those skilled in the art that many modifications and alterations may be made to the disclosed embodiment without departing from the invention. For example, one of skill in the art would understand that one could begin with a p-type substrate to manufacture a p-channel trench DMOS, which has silicon layer with complementary doping relative to the trench DMOS structure shown in FIG. 3. Also, all of the numbers provided for dimensions, temperatures, doping concentrations, etc. are for illustrative purposes only and may be varied to refine and/or enhance particular performance characteristics of the trench DMOS transistor. Hence, these modifications and alterations are intended to be within the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. A trench field effect transistor comprising:
 - a substrate having a first conductivity type;
 - a substrate cap layer extending over the substrate;
 - a substrate out-diffusion region having a first conductivity type extending over the substrate cap layer, the substrate out-diffusion region having a doping concentration which decreases in a substantially continuous manner across the substrate out-diffusion region;
 - a body region having a second conductivity type, which is epitaxially formed over the substrate cap layer;
 - at least one trench having a bottom and sidewalls, each trench extending through the substrate out-diffusion region, the substrate cap layer and the body region;

- a dielectric material lining the sidewalls and bottom of the at least one trench;
 - a conductive material lining the dielectric material and substantially filling the at least one trench; and
 - source regions having the first conductivity type positioned next to each trench within the body region.
2. The trench field effect transistor according to claim 1, wherein a thickness of the dielectric material at the bottom of the at least one trench is thicker than a thickness of the dielectric material on the sidewalls of the at least one trench.
 3. The trench field effect transistor according to claim 1, wherein the thickness of the dielectric material at the bottom of the at least one trench is thicker than a thickness of the substrate cap layer.
 4. The trench field effect transistor according to claim 1, wherein a thickness of the substrate out-diffusion region is less than or equal to one micrometer.
 5. The trench field effect transistor according to claim 1 wherein the conductive material extends through a substantial depth of the substrate out-diffusion region.
 6. The trench field effect transistor according to claim 1 wherein the dielectric material at the bottom of the at least one trench is a dielectric plug.
 7. The trench field effect transistor according to claim 1, wherein the substrate cap layer has the first conductivity type and a doping concentration less than a doping concentration of the substrate.
 8. A semiconductor device, comprising:
 - a substrate of a first conductivity type that forms a drain of the semiconductor device;
 - a substrate cap layer of the first conductivity type disposed over the substrate and having a lower concentration of dopant than that of the drain;
 - a substrate out-diffusion region of the first conductivity type extending over the substrate cap layer, wherein a concentration of dopant in the substrate out-diffusion region decreases substantially continuously from a surface of the substrate out-diffusion region at an interface between the substrate out-diffusion region and the substrate cap layer to an opposing surface of the substrate out-diffusion region;
 - an epitaxially-formed body extending over the substrate cap layer;
 - a plurality of trenches each having walls and a bottom and extending into the body, the substrate out-diffusion region and the substrate cap layer;
 - a dielectric layer formed on the walls and bottom of each trench; and
 - a conductive gate disposed within each trench over the dielectric layer.
 9. The semiconductor device according to claim 8 wherein the conductive gate in each trench extends through a substantial depth of the substrate out-diffusion region.
 10. The semiconductor device according to claim 8, wherein the dielectric layer at the bottom of each trench is a dielectric plug.

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